

# Automated Global Feature Analyzer – A Driver for Tier-Scalable Reconnaissance

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**Abstract**—For the purposes of space flight, reconnaissance field geologists have trained to become astronauts. However, the initial forays to Mars and other planetary bodies have been done by purely robotic craft. Therefore, training and equipping a robotic craft with the sensory and cognitive capabilities of a field geologist to form a *science craft* is a necessary prerequisite. Numerous steps are necessary in order for a science craft to be able to map, analyze, and characterize a geologic field site, as well as effectively formulate working hypotheses. We report on the continued development of the integrated software system AGFA: Automated Global Feature Analyzer<sup>®</sup>, originated by Fink at Caltech and his collaborators in 2001. AGFA is an automatic and feature-driven target characterization system that operates in an imaged operational area, such as a geologic field site on a remote planetary surface. AGFA performs automated target identification and detection through segmentation, providing for feature extraction, classification, and prioritization within mapped or imaged operational areas at different length scales and resolutions, depending on the vantage point (e.g., spaceborne, airborne, or ground). AGFA extracts features such as target size, color, albedo, vesicularity, and angularity. Based on the extracted features, AGFA summarizes the mapped operational area numerically and flags targets of “interest”, i.e., targets that exhibit sufficient anomaly within the feature space. AGFA enables automated science analysis aboard robotic spacecraft, and, embedded in tier-scalable reconnaissance mission architectures, is a driver of future intelligent and autonomous robotic planetary exploration.<sup>1,2</sup>

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## 1. INTRODUCTION

A multinational Mars exploration program is currently underway. Future missions involve multiple spacecraft, which are planned to orbit or land on Mars within the next decade. Varied instrumentation on these spacecraft have been generating huge datasets, and will generate unprecedented amounts of data in the future. In addition, as more and more missions spread out into the Solar System (e.g., Moon, Venus, Mercury, Titan, Pluto, various asteroids and comets), other potential problems arise, including a communications bottleneck as missions compete for downlink and uplink time, straining deep-space communications. This will result in extensive communication time lags, which translate into increased mission expenses. These and other potential problems using traditional onboard software make it infeasible to explore remotely large expanses of planetary surfaces independent from Earth control. Missions with traditional technologies will have to be replaced with autonomous “science craft” in order to make future missions more communication efficient, economical, and science effective, such as in situations where decisions, observations, and actions need to be made in-situ, e.g., to follow up on transient events. A traditional rover mission, for example, collects information at each stop along its planned traverse. This scenario is time and personnel intensive, and thus extremely costly. Just as significant, vital information may be bypassed along the traverse path. To construct a coherent history of what has transpired in the area of interest over geologic time, the reconnaissance field geologist moves from one patch of rock materials (or outcrops) to another over varying geological terrains. While tracking location and considering regional information previously compiled from published geological (e.g., stratigraphic, paleotectonic, paleoerosional, etc.), topographic, geophysical (e.g., gravity and magnetism), and hydrological (e.g., paleodischarge, drainage density, etc.) information, the field geologist gains a local

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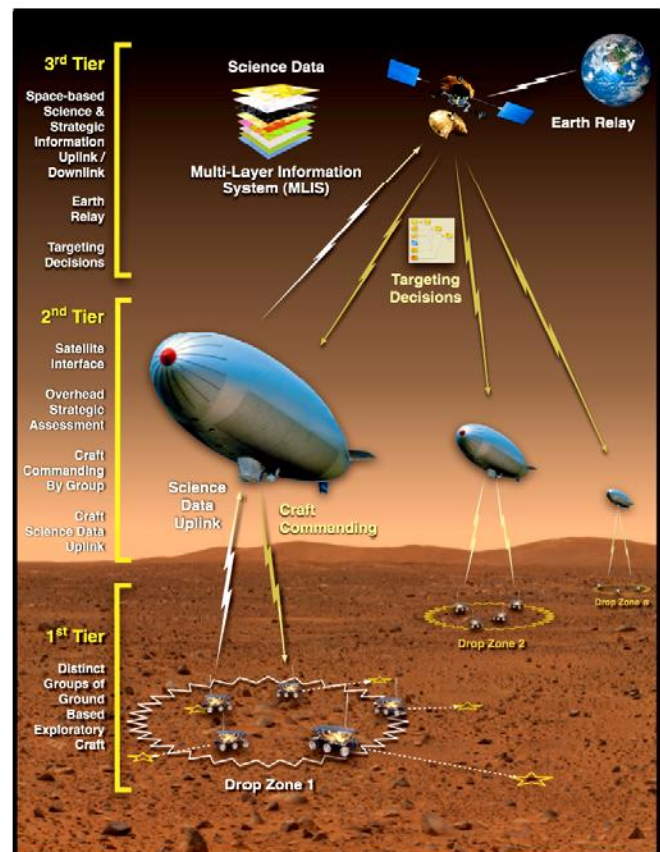
and regional perspective of the geological, hydrological, environmental, and climatological histories of a chosen study site by gathering essential field data while en route. A comprehensive understanding of the geology, hydrology, environment, and climate by the field geologist can optimally be achieved by coupling regional information with high-resolution information carefully compiled while covering large expanses.

Traditional missions to planetary bodies such as Mars, Venus, and Titan have tended to focus either on exploring a single site with a rover or lander, or global mapping, such as with an orbiter. The former analyzes a site in depth at the expense of a regional understanding, while the latter returns immense datasets that are time and personnel intensive to compile and evaluate, but often overlook the local and regional geological significance.

Robotic reconnaissance operations are called for in extreme environments such as space (including planetary atmospheres, surfaces, and subsurfaces), and hazardous or inaccessible areas on Earth. A fundamentally new planetary exploration mission concept, *Tier-Scalable Reconnaissance*<sup>®</sup>, originated by Fink et al. [1-6] (Fig. 1), replaces engineering and safety constrained mission designs that perform local ground-level reconnaissance with rovers and landers, or global mapping with an orbiter. The tier-scalable paradigm integrates multi-tier (orbit  $\leftrightarrow$  atmosphere  $\leftrightarrow$  surface/subsurface) and multi-agent (orbiter(s)  $\leftrightarrow$  blimps  $\leftrightarrow$  surface/subsurface agents or sensors) hierarchical mission architectures, and enables reconnaissance in real time (e.g., monitoring of transient events) on global, regional, and local scales for high science return and fully autonomous robotic missions, providing independence from human intervention, yet permitting manual override at any level. Tier-scalable reconnaissance not only introduces mission redundancy and safety, but enables distributed, science-driven, and less constrained reconnaissance (both spatially and temporally) of prime locations on Mars, Moon, Titan, Venus, and elsewhere. Such tier-scalable reconnaissance missions require a high degree of operational autonomy, such as [5]:

1. Automatic mapping of an operational area from different vantage points (i.e., space, airborne, surface, subsurface);
2. Automatic feature extraction and target/region-of-interest/anomaly identification within the mapped operational area, which includes intelligent data downlink;
3. Automatic target prioritization for follow-up or close-up (in-situ) examination;
4. Subsequent automatic (targeted) deployment and (concurrent) navigation/relocation of entire tiers or agents/sensors within tiers.

In place of astronaut geologists, the initial exploration of Mars and other planetary bodies will be conducted by robotic spacecraft. Therefore, training and equipping a robotic craft with the sensory and cognitive capabilities of a planetary/field geologist is a necessary prerequisite. Numerous steps are necessary in order for such a “science craft” to be able to automatically map, analyze, and characterize an operational area, and effectively formulate working hypotheses. Its main benefit will be the potentially increased science return during the respective mission lifetime and thus greater cost effectiveness.



**Figure 1. One embodiment of Tier-Scalable Reconnaissance<sup>®</sup>: Tri-level hierarchical multi-agent architecture for autonomous remote planetary exploration (from [5], after [1]).**

We report on the continued development of the integrated software system *AGFA*<sup>®</sup>: *Automated Global Feature Analyzer*<sup>®</sup>, originated by Fink at Caltech and his collaborators in 2001 (formerly *Automated Geologic Field Analyzer*<sup>®</sup> [7]). AGFA is an automatic and feature-driven target characterization system that operates in an imaged operational area, such as a geologic field site on a remote planetary surface. AGFA performs automated target identification/detection, feature extraction, feature classification, and target prioritization within mapped/imaged operational areas at different length scales and resolutions, depending on the vantage point (e.g., spaceborne, airborne, or ground). AGFA extracts features such as target size, color, albedo, vesicularity, and



angularity. Based on the extracted features, AGFA summarizes the mapped operational area numerically and flags targets of “interest”, i.e., targets that exhibit sufficient anomalous character within the feature space. AGFA enables automated science analysis for robotic spacecraft, and, embedded in tier-scalable reconnaissance mission architectures, is a driver of future intelligent and autonomous robotic planetary exploration.

## 2. RATIONALE FOR AUTOMATED GEOLOGIC

### CLASSIFICATION OF OPERATIONAL AREAS

In one embodiment of AGFA we focus in the following on the *geologic* classification of operational areas on a planetary surface, such as geologic field sites encountered by a planetary rover (or, to a much more limited degree, by a lander).

Why is it important to characterize the rocks, which compose the surface of a planet? The rocks reveal extensive information about the geological processes that transformed the surface. The *shape* of a rock can tell much about its location relative to its origin. Angular rocks tend to imply a short transport distance from their point of origin, while rounded ones tend to reflect a considerable distance involved from their place of origin. Alternatively, well-rounded rocks may also reflect the smoothing properties of various media, such as mud slurries or liquid water. The *orientation* of rocks may also reflect the presence of sustained liquid water. The *size* of rocks relative to other stones in their composite medium is another important indicator to the field geologist. If the rocks are of a common size, it may reflect a process, which sorted them as such. Very often on Earth, an outcrop, which displays the size of the rocks becoming finer as the field geologist moves up the stratigraphic column, is considered an important indicator of fluvial activity, including floods that deposited the materials. Alternatively, if the rocks are a mix of varying sized, shaped, and textured rock materials (e.g., boulders to grains of sand and/or muddy matrix), a catastrophic depositional process such as mass wasting might be a viable explanation for the emplacement of the materials. The *color* of rocks is also an important indicator of origin. Various lithologies such as basalt and sandstone have a characteristic range of colors they may display, depending on chemical composition and the environmental/weathering conditions during and after emplacement. The surface and surface *texture* of a rock also holds clues to its origin. If the rock is composed of other smaller rocks (also known as a composite rock and/or conglomerate), it may imply certain chemical bonding and/or depositional processes that can only occur in certain environments. If the rock displays fine layering, it may be sedimentary in nature, which also implies certain environments for its formation. Whether a rock is smooth or vesicular, combined with other rock

attributes, may also be indicative of its origin. A highly vesicular, dark gray, sub-angular to angular rock, especially with phenocrysts, for example, would be best explained by a volcanic origin.

A synthesis of these important rock features listed above and others will in turn provide a greater understanding of rock types, process-driven activities, depositional environments, potential sources for the observed rock materials, and a coherent interpretation of the past geologic evolution.

It should be noted that during the reconnaissance of a geologic field site it is not so important to capture all the details, e.g., number of rocks and rock types, but to get a first good estimate and overview of what is there. Based on this first, “rough” estimate, a *working hypothesis* may be drafted, and based on this hypothesis, further corroborating or refined information may have to be gathered within the same or, in addition, within other, potentially distant operational areas. This “general procedure” - the *geologic approach* - led to the creation of AGFA.

## 3. METHODS & TECHNICAL IMPLEMENTATION

The aim of this paper is to undertake an important foundational step in developing and implementing an innovative and integrated software system, AGFA, for automated (science) analysis of operational areas. AGFA performs automated mapping/imaging, feature extraction, feature analysis, and target prioritization within operational areas at different length scales and resolutions, depending on the vantage point (e.g., spaceborne, airborne, or ground).

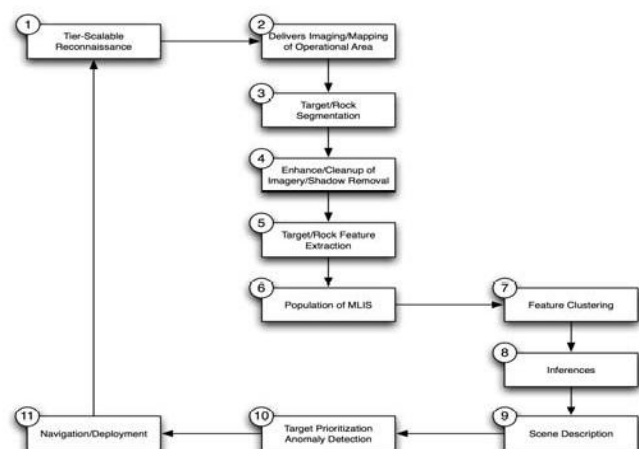


Figure 2. AGFA Operational Diagram (after [7]).

Employed by a planetary explorer such as an orbiter, balloon/blimp, or rover, AGFA (1) automatically maps and characterizes target/rock materials in the imaged operational area (e.g., geologic field site), both on the ground and from the air, including size (boulder, cobble, pebble), color, albedo (light, medium, dark), texture (vesicular or smooth),

and shape (degree of angularity - angular, subrounded, rounded), and (2) identifies autonomously (i.e., exclusively feature-driven as opposed to "biased", human hypothesis-driven) "interesting" or anomalous rocks based on the extracted rock features. AGFA is an extensible analysis and classification framework, which is not limited to the currently implemented suite of methods that are discussed in the following (see also "Discussion & Outlook"). We describe briefly the functional steps of AGFA and how they build on each other (Fig. 2; the detailed mathematical underpinning of AGFA will be provided elsewhere).

1. **Imaging/Mapping** – Images of the operational area under investigation are obtained at different length scales and resolutions (Fig. 3), depending on the vantage point (e.g., spaceborne, airborne, or ground).



Figure 3. Imaged operational area, in this case a geologic field site as seen by a planetary rover (from [7]).



Figure 4. AGFA-performed image segmentation to identify targets (here: rocks) within the imaged operational area (from [7]).

2. **Rock Segmentation** – To segment out the rocks from the background of an imaged operational area we have developed and implemented several image segmentation schemes such as *k-means* and *histogram-based segmentation* for the purpose of clustering rocks and the background into separate clusters (Fig. 4).
3. **Imagery Enhancement/Clean-up** – Statistics based on the luminance and chrominance of the foreground surrounding a rock are derived and coupled with spatial constraints to remove pixels that have a high probability of being cast shadows.
4. **Target Feature Extraction** – Targets/rocks that were identified in the previous steps are further characterized by extracting features such as size, color, albedo, texture, and shape descriptors. We have developed modules that currently give us the following feature measurements for each rock present in the imaged operational area:

- *Size* – The size of each rock is estimated using the image size (camera field of view) and the distance from the camera to the surface of the operational area. Rock sizes are currently subdivided into three classes: pebbles (2cm-10cm), cobbles (10cm – 20cm), and boulders (>20cm). Rocks smaller than 2cm are considered to be part of the background/matrix and are currently not characterized. The size and the following features would be equally extractable though when looking at microscopic images of operational areas.
- *Color* – The RGB color space is used in this module. The average RGB color of the rock is computed from its respective intensity distribution in each of the color channels.
- *Albedo* – The brightness or shade of an object provides significant information in its own right. The albedo is currently quantified into three ranges: light, medium, and dark. The perceived brightness of an object is a function of the incident light.
- *Texture* – Image texture is characterized by the spatial frequency and orientation of brightness variation in a region. Image texture can be used as an indicator of the three-dimensional surface texture of a rock. The resulting texture feature vector can be subdivided into classes indicating, for example, smooth, slightly to moderately vesicled, and highly vesicled rock surfaces. We have employed Gabor filters of different orientation and scale.



- *2D Shape Characterization* – To characterize the shape of a target/rock we have developed and implemented the following modules:
  - a. *Ellipse Fit* – For each identified target/rock the best-fit ellipse is calculated to describe its shape, thereby obtaining measurements for the *major axis*  $a$ , the *minor axis*  $b$ , and the *geometric eccentricity*  $e$ , defined as the ratio of the semi-minor axis of the ellipse to the semi-major axis. The spatial orientation of the major/minor axes together with the absolute orientation of the operational area images allow for the calculation of an orientation vector field for targets/rocks in that region of interest, contributing to geologic process working hypotheses.
  - b. *Angular/Roundness* – This measure indicates the sharpness of the corners of an object and the angularity of its edges. It is calculated as the deviation of the best-fit ellipse and the actual object outline. We distinguish between angular, sub-rounded, and rounded targets.
  - c. *Eccentricity* – The geometric eccentricity is defined as the ratio of the minor to the major axis of the best-fit ellipse for a given shape. It is a measure for the elongation of a particular object.
  - d. *Extent* – Extent is defined as the ratio of pixels that are inside the object, divided by the area of the bounding box around the object.
  - e. *Moments* – Moments are shape encoders and can be used to distinguish between different rock shapes. At present, we calculate 7 HU and 10 Alt moments for each rock.
- *Spectral Data* – As a future extension to the AGFA software system we envision to incorporate a rock spectra software module that compares a particular observed rock spectrum to a database of stored, known rock spectra via artificial neural networks or stochastically optimized spectral retrieval procedures (e.g., [8]) to help determine the rock composition.

In applying steps 1 through 4, AGFA obtains *feature vectors* for all identified targets/rocks within the imaged operational area (Fig. 5). These feature vectors are subsequently used by AGFA to classify targets/rocks, and to identify anomalies. It is essential to note that this is done in

an objective, i.e., exclusively feature-driven and thus unbiased automatic manner. In contrast to Artificial Intelligence (AI) schemes (e.g., [9, 10]), AGFA does not depend on expert-defined rule sets, but operates instead within the classification-inherent feature space itself.



**Figure 5. Identified targets (here: rocks) within an imaged operational area and their respective extracted feature vectors, derived by AGFA for the ground level. At this level, the targets can scale from microscopic soil particles to large rocks. For airborne and spaceborne vantage points, the targets scale from large rocks to mountain ranges (from [7]).**

5. **Feature Summary** – The imaged operational area is described by first identifying regions of targets/rocks with common properties and subsequently by summarizing the values of the properties of the targets/rocks in these identified regions.
  - *Characterization of operational area:* Having quantified the properties of individual rocks and identified regions of rocks, we summarize the properties of the imaged operational area. The percentage of area covered by rocks for each of the categories defined for all of the descriptive properties – size, color, albedo, texture, and shape can be calculated. In addition, the sorting of the rocks based on size can be evaluated (e.g., rock-size distribution).
6. **Feature Clustering** – The extracted, individual target feature vectors undergo a normalization process and are subsequently clustered into the natural number of clusters.
7. **Target Prioritization** – Multiple prioritization scenarios can be conceived to evaluate the importance of individual targets or combinations of targets to be further examined during reconnaissance missions, which differ in their respective level of complexity.

These scenarios can range from simple feature-based or feature-clustering-based prioritization [11-13] to prioritization via context-based clustering [14].

Recently, more advanced prioritization frameworks [15] have been developed using previously acquired, coarse feature/reconnaissance data that was pre-clustered using either general purpose clustering algorithms [11-13]) or clustering algorithms associated with special-purpose models [14]. This advanced class of algorithms facilitates (1) the selection of single or multiple targets, and (2) the selection of instruments used for the close-up examination of these targets in an operational area for potential information gain about the operational area under investigation [15].

8. **Inference & Anomaly Detection** – Based on the clusters obtained from the previous steps, two flags are calculated, the *distance flag* and the *number flag*:

- *Distance Flag* – The distance flag compares the distance between the cluster centers to their respective size in the feature space: if the sum of the respective largest eigenvalue for each cluster, obtained via Principal Component Analysis (PCA), is less than the distance between the centers of the respective two clusters, then the distance flag is set to *red*, else *green*.
- *Number Flag* – The number flag tries to estimate how abnormal the population size of a cluster (i.e., number of cluster members) is compared to another: If there is a cluster, which is only a fraction of the size of the cluster it is compared to, then the number flag is set to *red*, else *green*.

The most interesting cases arise from a *red-red* flag combination, indicating *absolute anomalies*. *Relative anomalies* are indicated in cases of *red-green* or *green-red* flag combinations. The least interesting situations are given by a *green-green* flag combination, in which case *no anomalies* are indicated. More refined classification schemes, other than just three decision cases, can be applied (see also [9, 10] for real-valued decision functions).

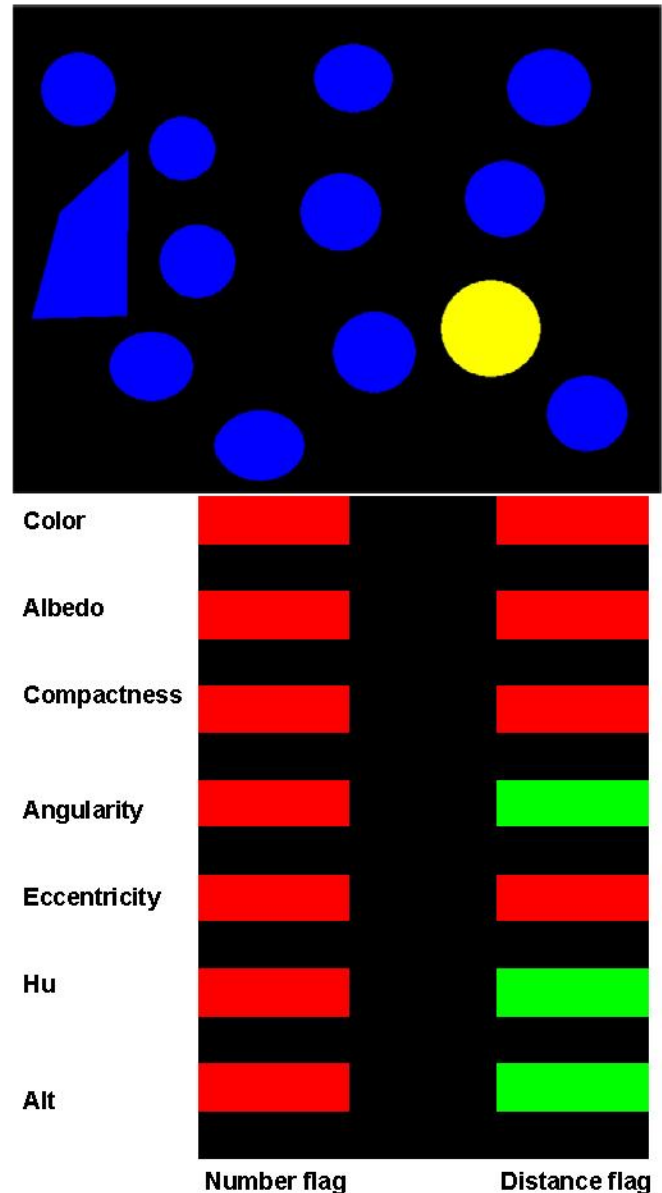
Based on AGFA’s feature summary, inference & anomaly detection, and resulting target prioritization, subsequent automatic (targeted) deployment and navigation/relocation of entire tiers or agents/sensors within tiers of a tier-scalable reconnaissance mission architecture can occur (see also “Discussion & Outlook”). As such, AGFA becomes the actual driver for tier-scalable reconnaissance missions.

We have developed an overall architecture for AGFA in both MATLAB and C, wherein the user can interactively choose the features to be calculated. AGFA can also operate in batch-mode, i.e., automatically generating feature vectors

according to a pre-specified list of features without any further user intervention.

## 4. RESULTS

In the following we present two example classifications performed by AGFA in its *geologic* embodiment: (1) an artificial scene (Fig. 6) to demonstrate in simple terms how AGFA operates, and (2) a “real-world” application of AGFA (Fig. 7).



**Figure 6. Top:** Artificial scene, containing several targets that differ in shape, color, and number. **Bottom:** AGFA-classification result, indicating (1) absolute anomalies in the color, albedo, compactness, and eccentricity feature spaces, and (2) relative anomalies in the angularity and in the shape-encoders Hu and Alt.



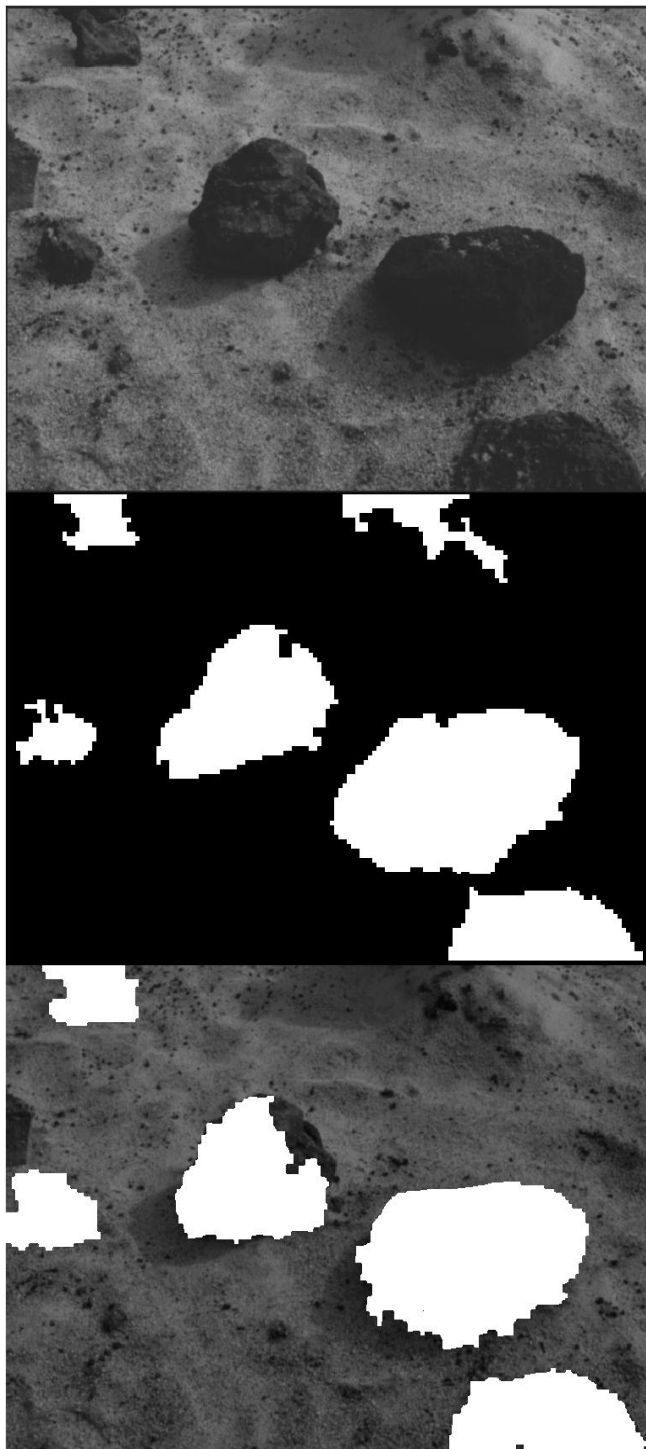
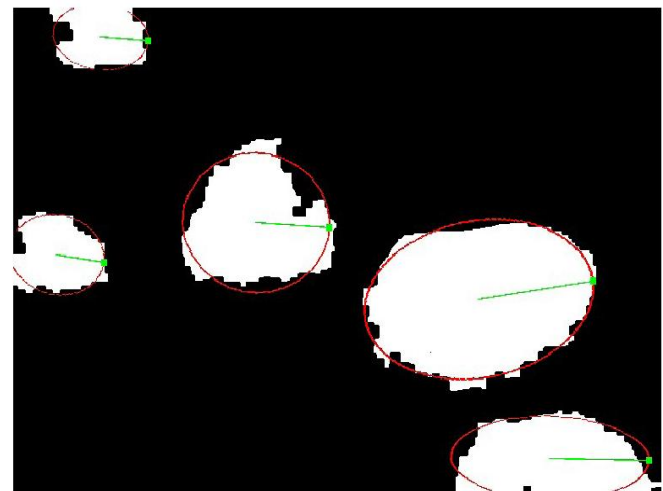


Figure 7. The six picture panels depict an example analysis sequence of AGFA, performed on an image of a more realistic scene. *P1*: original image of operational area; *P2*: identified/segmented target areas (rocks); *P3*: shadow removal in identified rock areas; *P4*: ellipse fitting of identified rock areas together with orientation of semi-major axes; *P5*: numerical feature summary of identified targets; and *P6*: resulting AGFA-classification of entire imaged operational area: in this case, no anomalies detected.



Features	Segment Nos.				
	1	2	3	4	5
Color					
R-channel	29.282	31.301	29.98	40.448	43.501
G-channel	14.996	18.073	20.686	25.78	27.831
B-channel	17.439	21.639	24.899	29.231	31.612
Albedo	19.545	22.434	23.944	30.558	32.947
Angularity	1.278	1.4225	1.0527	1.296	1.2859
Eccentricity (b/a)	0.6148	0.8896	0.3600	0.7335	0.8363
Extent	0.7226	0.6235	0.7603	0.6900	0.7249
Major Axis (pixels)	130.49	78.618	116.27	50.695	50.212
Minor Axis (pixels)	80.229	69.94	41.862	37.184	31.948
Area (# pixels)	33376	17171	14753	5851	4854
Orientation (degrees)	8.2634	-3.5274	-1.3297	-8.8036	-4.8608
World Size (D = 5m, Angle = 45 deg)	Size of minor axis (b) in meters				
	2.15	1.88	1.12	1.01	0.86
	Size of major axis (a) in meters				
	3.51	2.12	3.12	1.44	1.46

Color

Albedo

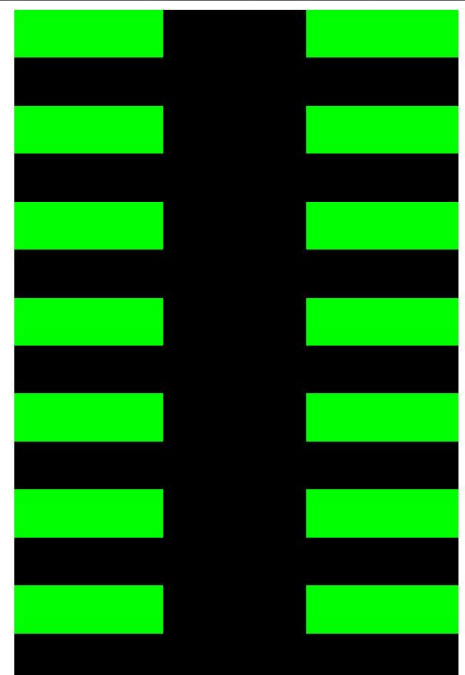
Compactness

Angularity

Eccentricity

Hu

Alt



Number flag

Distance flag

## 5. DISCUSSION & OUTLOOK

There have been several elements of autonomous/automated science analysis packages previously proposed and developed such as in [16]. These elements have generally been applicable only under specialized conditions and must be applied manually. An autonomous system for a characterization of an operational area (here: geologic field site) that incorporates a variety of elements to develop a comprehensive understanding of a region has not been demonstrated to the best of our knowledge.

In contrast, AGFA is a first-of-a-kind approach towards a fully automated (no human-in-the-loop) and integrated software system that performs image segmentation of an operational area, such as a geologic field site on Mars, Moon, Titan, or Earth, thereby acquiring (science) targets, followed by a comprehensive feature extraction (e.g., shape, size, color, albedo, texture, angularity, eccentricity, compactness, extent) for the identified targets, which is then followed by an objective and self-contained (i.e., exclusively feature-driven as opposed to "biased", human hypothesis-driven) anomaly detection, employing a variety of clustering algorithms such as sequential and hierarchical clustering algorithms. The AGFA software system enables a fully automated and comprehensive characterization of an operational area such as a geologic field site on a remote planetary surface.

An additional strength of AGFA is the fact that, when embedded into a tier-scalable reconnaissance architecture, it enables, for the first time, the intelligent exploration of remote planetary surfaces not only from the ground but from the air and space as well. For example, aerial reconnaissance from a balloon, blimp, airship, or glider on Mars, Titan, or Venus in addition to or in place of ground-based rover units, could cover a tremendously larger area of the surface in a much shorter time than previously possible [1-6, 17, 18].

The study of geology is fundamentally different from the other sciences, such as physics or chemistry. Whereas these fields rely on fundamental laws derived from mathematics and experimentation, geology has always been the art of inferring the natural history based on the signs in the present. Geology has discovered many unique and amazing phenomena, from plate tectonics (continental drift) to the former existence of gigantic glacial ice sheets. But none of these processes was discovered by *direct* observation. None was determined from fundamental laws. All the advancements of understanding the natural world that geology has achieved have come from abduction or retrodution [19], with subsequent deduction. The deduction is usually never made from a single piece of evidence, rather, it is a suite of different and unique evidence, and often is difficult to discern in the field. It is for these reasons that we propose any comprehensive and

accurate study of planetary surfaces (e.g., Mars) must be conducted in the manner that field geology has always operated. Given the cost and difficulty of sending human geologists into space, the next best thing would be an autonomous robotic science craft or several science craft as part of a tier-scalable mission architecture, equipped with the sensory capability and the ability to "reason" like a field geologist.

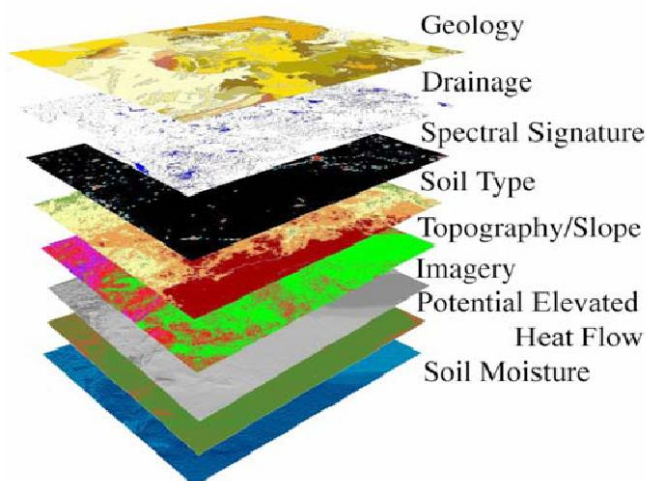
The reasons for this necessity are not always obvious. How does one characterize an area in terms of its geologic history? Examining the rocks, though having the potential to yield significant information, may not be enough to confidently formulate working hypotheses of the processes-related activities and environmental, hydrological, and climatological conditions that contributed to the surface expression observed by the science craft. First, the science craft must be aware of the context it is in. To a field geologist, the implications of the materials around him can mean very different things if he is in a canyon as opposed to a mountaintop. Next, he must be aware of the relationships between the materials around him. Can they be grouped into categories of similar origin or substance? Can he identify different levels or terraces that may differentiate some materials from others? How do different materials relate to each other? Does one type of material (called a unit or layer) lie on top or below another? Or are the units tilted, folded, or show evidence of inversion? What are the types of landforms that occur in the region of study, and how do these landforms occur in time and space? All this information must be obtained, but much more importantly, analyzed as to the relationships between each other and the area they occupy. This is absolutely critical. This kind of analysis was achieved with the Pathfinder rover mission, but only after the information was sent back to Earth and analyzed by teams of human geologists. Considering the size and incredible differences in terrain and material composing the surface of Mars [20-25], this method would not allow for a thorough understanding of the planet in a manageable time span. Instead of this time and energy consuming process, the advantage of an autonomous robotic field geologist becomes apparent.

Our goal is to eventually merge AGFA with other innovative tools for autonomous science analysis of geological field sites, including GIS-based multi-layer information, which includes published geological, topographic, geophysical, mineralogic, and hydrological data sets at local, regional, and global scales. This *Multi-Layer Information System (MLIS)* [1-3] (Fig. 8), containing geologic, structural, and erosional information, combined with AGFA capabilities could help unravel complex geologic histories at local, regional, and global scales that can be readily updated with information obtained from future tier-scalable reconnaissance missions (Fig. 1).

Although the focus of this paper is mainly on geologic classification of operational areas, future embodiments of



AGFA will address (1) geophysical, (2) geochemical, (3) (hyper-)spectral, and (4) biological classifications of operational areas for enhanced geologic and exobiologic exploration.



**Figure 8.** Example layers, in part delivered by AGFA, which make up the *Multi-Layer Information System (MLIS)* (from [1-3]).

AGFA is currently undergoing field testing aboard ground-based robotic platforms (Fig. 9) [4, 5] and will be tested in the near future aboard airborne platforms, such as helicopters and blimps, as part of the tier-scalable reconnaissance mission test bed at Caltech [4]. As for the spaceborne perspective, AGFA will be tested on satellite and orbiter imagery, and for a close-up (microscopic) ground perspective, it will be tested on microscopic images, such as those delivered by the Mars Exploration Rovers (MER) Spirit and Opportunity (e.g., [26]).



**Figure 9.** 4WD remote controllable robotic platform as a representative mobile ground-tier agent of the tier-scalable reconnaissance mission test bed at Caltech (from [4, 5]). This platform is being used for testing AGFA in an operational environment.

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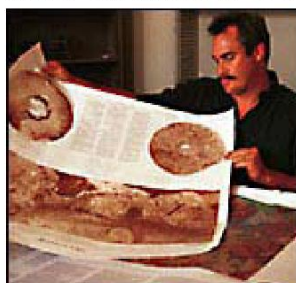




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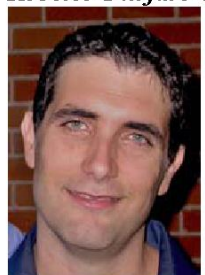


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